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Comparison of Airborne Electromagnetic Induction and Subsurface Radar Sounding of Freshwater Bathymetry

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May 1993

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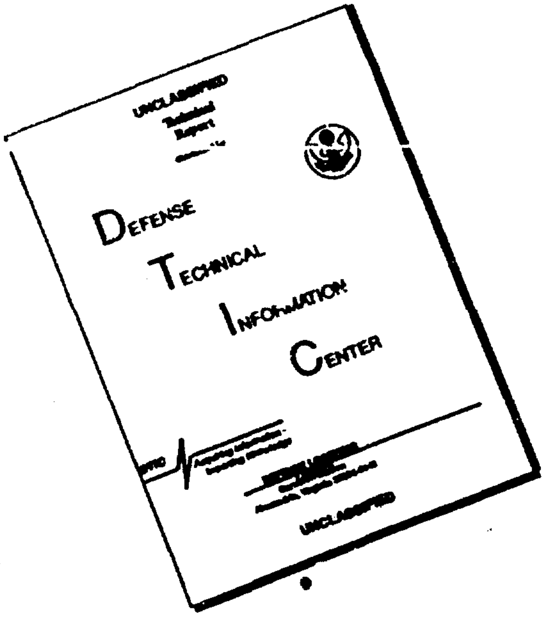

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Abstract

A helicopter-borne electromagnetic induction (EMI) sounding system, operating at frequencies of 0.9, 4.6 and 33 kHz, was used in an attempt to profile freshwater bathymetry under an ice-covered lake. The EMI sounding results were compared with bathymetric measurements made by tape sounding and impulse radar sounding (~120 and 280 MHz). As expected, the radar-measured depths were in excellent agreement with the tape measurements. The EMI bathymetry determinations were not representative of the lake bed topography. It is speculated that the EMI system was affected by an electromagnetic response from other than the freshwater/sediment interface.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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May 1993

Prepared for
NAVAL OCEANOGRAPHIC AND ATMOSPHERIC RESEARCH LABORATORY

PREFACE

This report was prepared by Austin Kovacs, Research Civil Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, and J. Scott Holladay, Manager, Research and Development, Aerodat Ltd., Mississauga, Ontario, Canada.

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Comparison of Airborne Electromagnetic Induction and Subsurface Radar Sounding of Freshwater Bathymetry

AUSTIN KOVACS AND J. SCOTT HOLLADAY

INTRODUCTION

Helicopter-borne electromagnetic induction (EMI) sounding has recently been used to profile sea ice thickness and the depth of seawater under the ice canopy (Kovacs et al. 1987, Kovacs and Holladay 1990), shallow ocean bathymetry (Won and Smits 1987) and the depth of a lens of fresh water resting on the seawater "table" in a North Sea barrier island (Sengpiel 1983). This bathymetric sounding success encouraged us to try the technology for sounding the bathymetry of an ice-covered lake. This environment represents a difficult one for EMI sounding because of the generally low conductivity contrast between the lake water and the bottom material. This difficulty was further compounded by the EMI system available to us, which had lower operating frequencies than desirable for this sounding application.

Impulse or subsurface radar sounding has been used since the early 1970s for profiling the thickness of snow (Kovacs and Gow 1975), ice (Blindow and Thyssen 1986), frozen ground (Annan and Davis 1976, Kovacs and Morey 1978) and various geologic horizons, as well as for profiling freshwater bathymetry (Kovacs 1978 and 1991, Ulriksen 1987 and Sellmann et al. 1992). Previous experience with this sounding technology indicated that there would be no difficulty profiling freshwater bathymetry either from the ice surface or from a helicopter (Kovacs 1978). Therefore, we used the radar system to provide through-the-ice bathymetry information against which the EMI sounding results would be compared.

This report gives an account of the limited field trial results obtained using both the impulse radar and EMI systems for sounding lake bed topography through an ice cover.

STUDY SITE

The field trials were conducted at Lake Nipissing, Ontario, Canada. A 1.07-km-long survey line was laid out from near a small rock island to a point just past an approximately 2-m-diam. bedrock feature that protruded about 0.5 m above the ice surface (Fig. 1). During the winter, the water level of Lake Nipissing is lowered; therefore, this bedrock feature is probably at or just below the level of the summer water surface.

Nine stations were established at various positions along the survey line. At each station, snow depth, ice thickness and the water depth under the ice were determined by use of a drillhole and tape measurement (Fig. 2). The snow plus ice thickness and the depth of water under the ice are listed in Table 1. At each station, black markers were set on the snow surface. These were used for flight track alignment by the helicopter pilot during the airborne EMI sounding runs and for reference points that were recorded on the flight path recording system. The stations were also reference points used during the impulse radar survey.

RADAR SOUNDING SYSTEM

Ground-penetrating impulse radar sounding systems typically operate in the VHF and UHF frequency bands (between 30 MHz and 3 GHz) where 300 MHz is the frequency separating the two bands. In the Geophysical Survey Systems Inc. (GSSI) subsurface radar system used, an impulse of electromagnetic energy of a few nanoseconds duration is transmitted from an antenna into a material. The transmitted wavelet has a broad band, with a frequency bandwidth on the order of

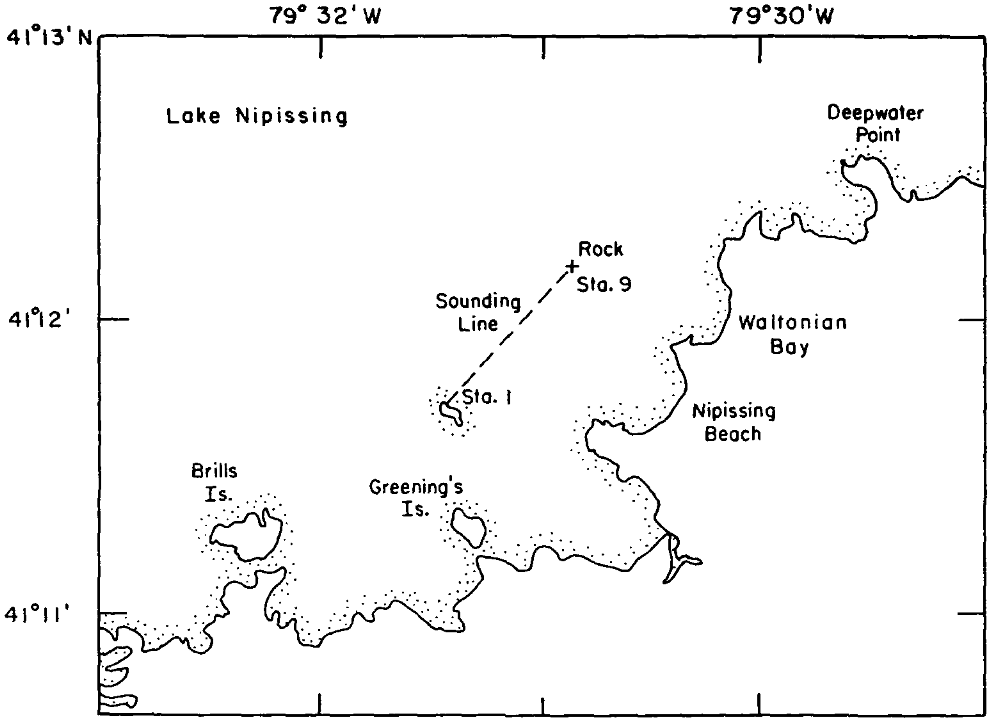


Figure 1. Location of survey line along which airborne electromagnetic and impulse radar sounding were made at Lake Nipissing, Ontario, Canada.

about 100 MHz at the -3-dB power level. The center frequency of the transmitted wavelet spectrum (the center frequency) and the time duration of the emitted energy in air are functions of the size of the antenna and its dampening characteristics as well as the impulse transmitter characteristics. A portion of the energy will be reflected when the electromagnetic energy is radiated from an antenna into a material and impinges on a horizon or object of dielectric contrast. The amount of energy

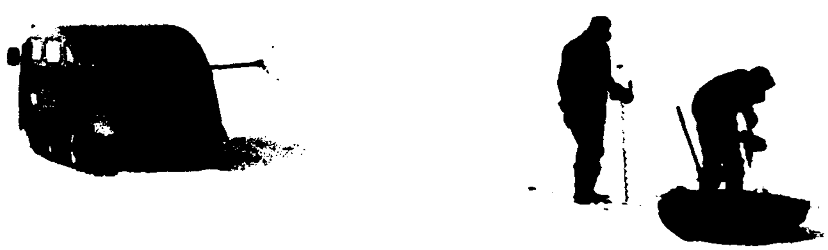


Figure 2. Hole drilling for snow and ice thickness measurement and the oversnow vehicle used for towing the radar antennas on Lake Nipissing.

Table 1. Lake Nipissing survey line station snow plus ice thickness and water depth under the ice as determined by tape measurement to the nearest 5 cm.

Ice station	*Snow and ice thickness (m)*	*Sub-ice water depth (m)*
1	0.80	1.20
2	0.85	4.55
3	1.00	5.50
4	0.85	6.55
5	0.85	7.05
6	0.85	7.25
7	0.85	5.90
8	0.85	3.90
9	0.80	1.65

reflected back to the receiver will depend on the distance and the size, roughness and slope of the target, as well as on the electrical contrast at the interface. The energy not reflected back may be scattered or will continue onward, where the process may be repeated or until the energy is completely attenuated. The depth of penetration depends on the electrical properties of the subsurface materials: for example, the relative dielectric constant, which governs the wavelet velocity; the conductivity, which governs energy attenuation; and on-beam spreading losses. The reflected energy sensed by the receiver is frequently displayed in real time on a graphic recorder, in a manner similar to a time-domain acoustic sub-bottom profiling system used to profile marine sediments. This is how the impulse radar system was used in this field study. The data may also be displayed in real time on a monitor or stored on magnetic tape or in digital memory for later analysis.

The primary quantity measured is the two-way travel time between various targets or subsurface interfaces. The radar system was calibrated using the tape-measured distance from the snow surface to the lake bottom. In this procedure, the two-way travel time of the electromagnetic wavelet from the snow surface to the lake bed and back was converted to a depth scale on the graphic record.

The radar system used was a modified GSSI System 3. The controller and graphic recorder unit were placed in an oversnow vehicle. Two radar antennas, either a model 3105 (approximately 280-MHz wavelet center frequency in air) or a model 3020 (approximately 120-MHz wavelet center frequency in air) were towed, one at a time, behind the vehicle as shown in Figure 2.

ELECTROMAGNETIC INDUCTION SYSTEM

A standard four-frequency airborne electromagnetic induction sounding system, made by Aerodat Ltd., was used. The antenna platform (bird), suspended 30 m below the helicopter (Fig. 3), was about 0.5 m in diameter and 7 m long. Within this cigar-shaped bird were four transmit and receiver coil pairs. Each coil pair was spaced 6.45 m apart and positioned in either a coaxial or coplanar alignment. The operating frequencies were 930 and 4600 Hz for the two coil pairs aligned coaxially and 4600 and 33,000 Hz for the two coil pairs aligned horizontally coplanar.

In an EMI system the transmitted electromagnetic field induces eddy currents in a nearby electrically conductive mass. As a result, a secondary magnetic field arises that produces a voltage, proportional to the secondary magnetic field, at the receiver. The received voltage amplitude and phase

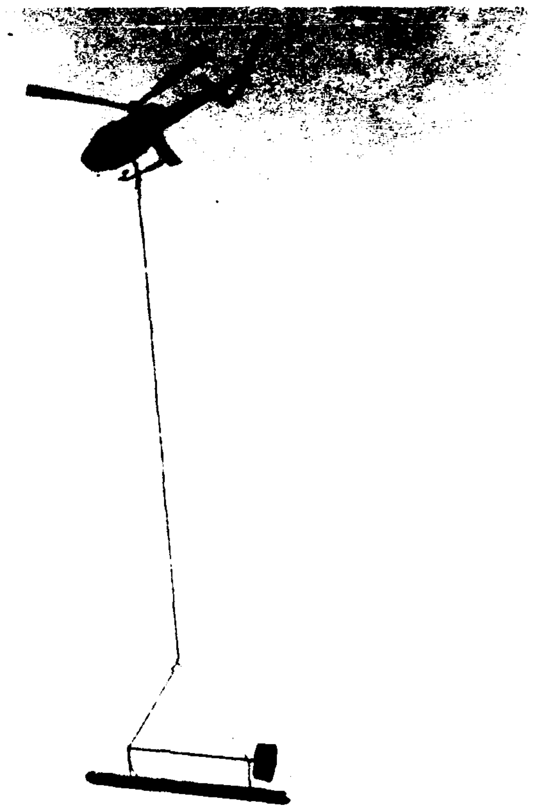


Figure 3. View of helicopter and the towed electromagnetic induction sounding system's antenna platform (bird).

are functions of 1) transmitter coil orientation, 2) position with respect to the receiver coil and radiated electromagnetic field strength, 3) the conductivity, distance and relief of the conductive surface with respect to the transmitter, and 4) sensitivity, orientation and distance of the receiver coil with respect to the conductive interface (Kovacs and Holladay 1990). Since the electromagnetic response measured at the receiver is related to the distance between the bird and the conductive interface, an accurate measurement of this response can provide a very good estimate of this distance. If the electromagnetic response from the lake bed can be detected and properly analyzed, then the resulting bird-to-lake-bed distance should be determinable. When this distance is subtracted from the bird height above the snow-covered lake ice surface, as measured with a laser altimeter mounted in the bird, then an estimate of the lake depth can be made. More detailed information on helicopter-borne EMI sounding systems and the related theory of operation can be obtained from the lists of textbooks and journal articles on the subject provided by Palacky (1986), as well as the papers previously referenced by Kovacs et al. (1987) and Kovacs and Holladay (1990).

SURVEY RESULTS

A radar sounding profile was made from station 1 to station 9. From station 9 the sounding run continued east-southeast to the shore at Waltonian Bay (Fig. 1). The 280-MHz antenna was used for this sounding run. The annotated radar graphic record is shown in Figure 4. In this record the snow surface and ice bottom are shown, as is the lake bottom topography. The sub-ice targets between stations 5 and 6 at a depth of about 0.5 m and 1 m are believed to be fish. The deeper reflection at about 1.5 m is believed to be a double reflection but may indeed be another fish. As expected, the radar provided a good profile of the lake bottom relief.

Another radar profile was made from just before station 1 to just beyond station 9. This record, made using the 120-MHz antenna, is shown in Figure 5. This record shows that the sediment

Figure 4. Radar profile of snow plus ice thickness and under-ice bathymetry along survey line from stations 1 to 9 and from station 9 to the Waltonian Bay shoreline shown in Figure 1. The 280-MHz antenna was used for this sounding.

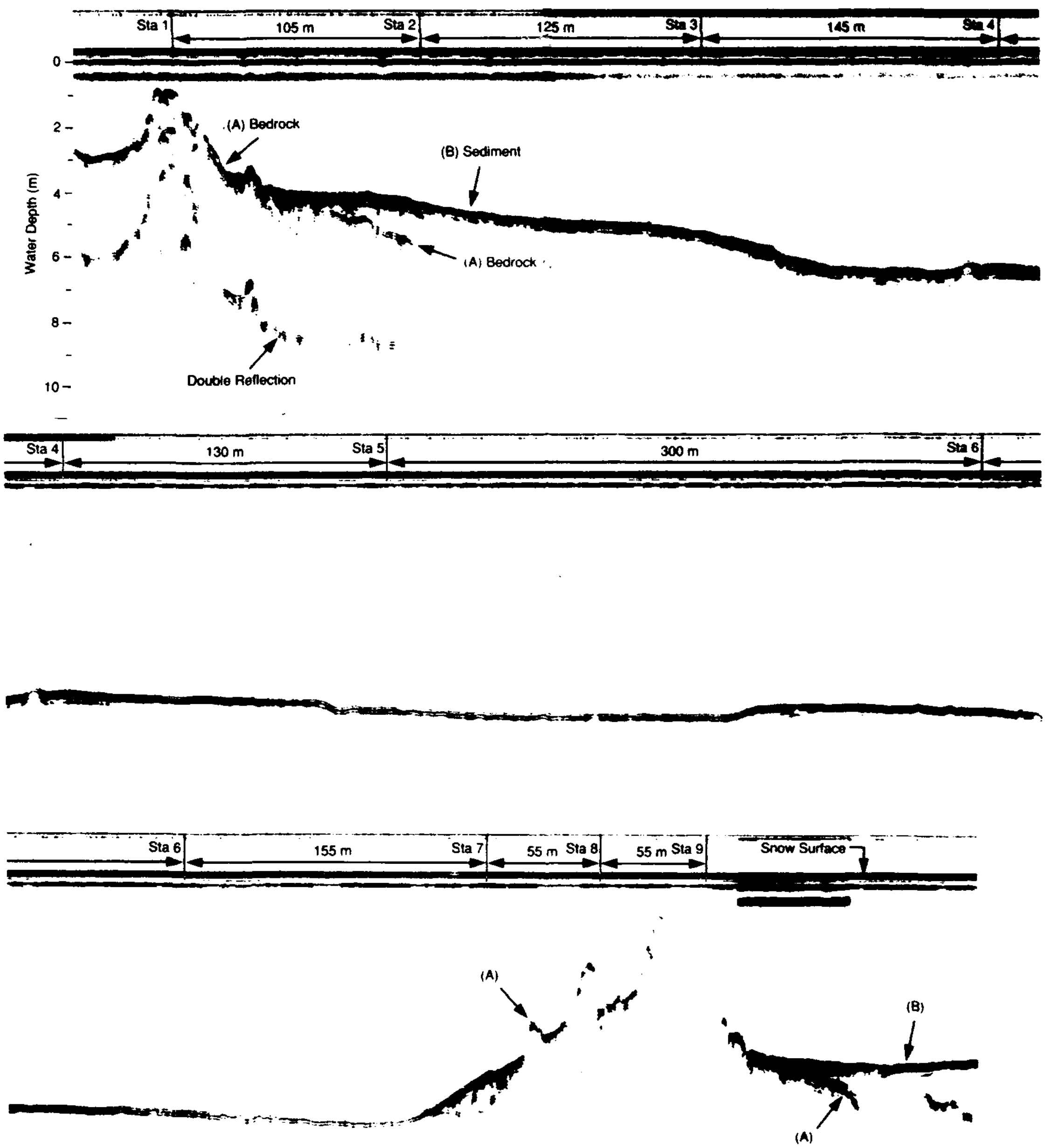
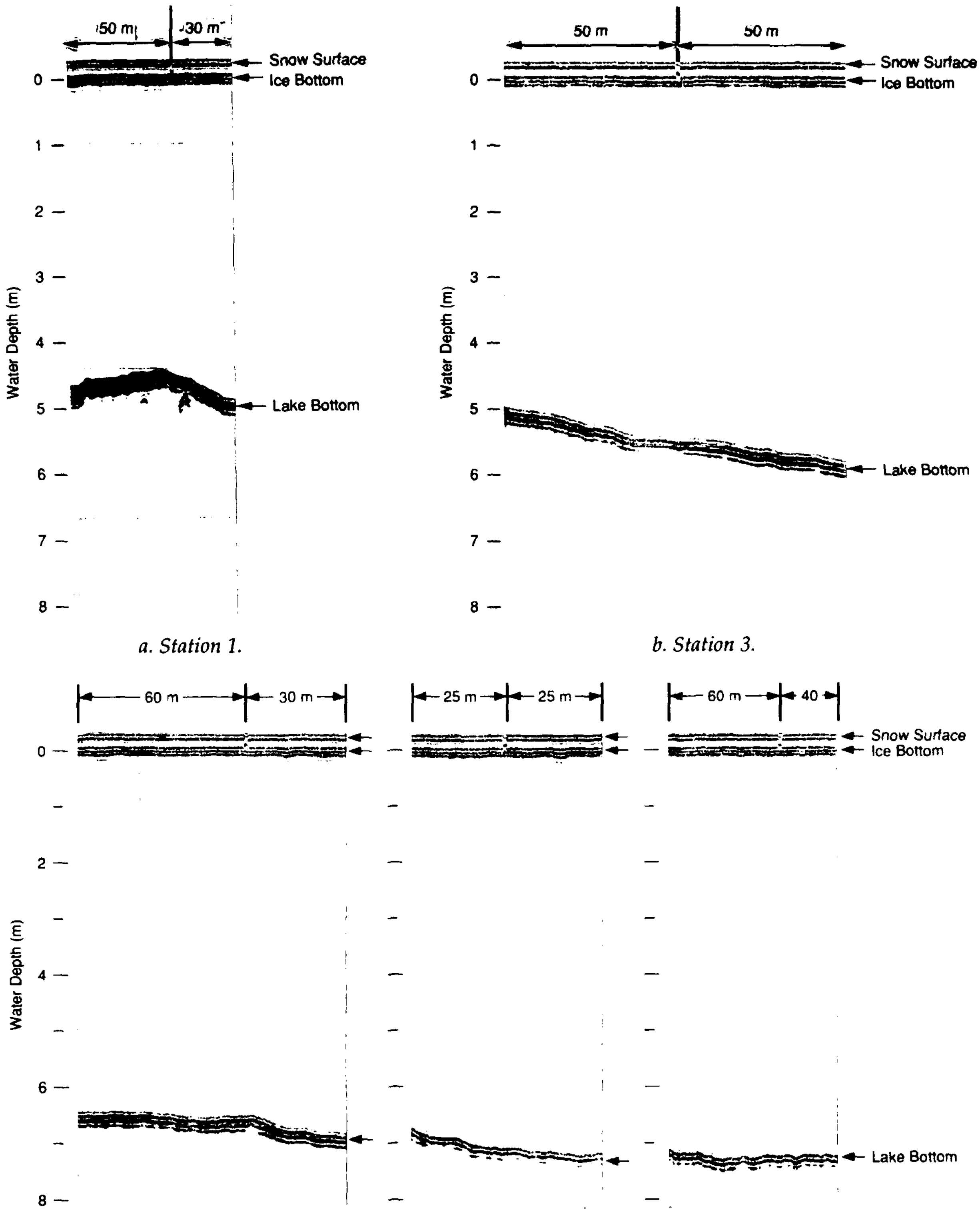


Figure 5. Radar profile of snow plus ice thickness along survey line using the 120-MHz antenna. Note the relatively mild bottom relief between stations 2 and 7 and the sub-bottom signature of the bedrock to the left of station 2 and to the right of station 9.



a. *Station 1.* b. *Station 3.*

c. *Station 4.* d. *Station 5.* e. *Station 6.*

Figure 6. Short radar sounding records made perpendicular to the survey line at stations 2–6 to verify that the bottom was relatively uniform in relief.

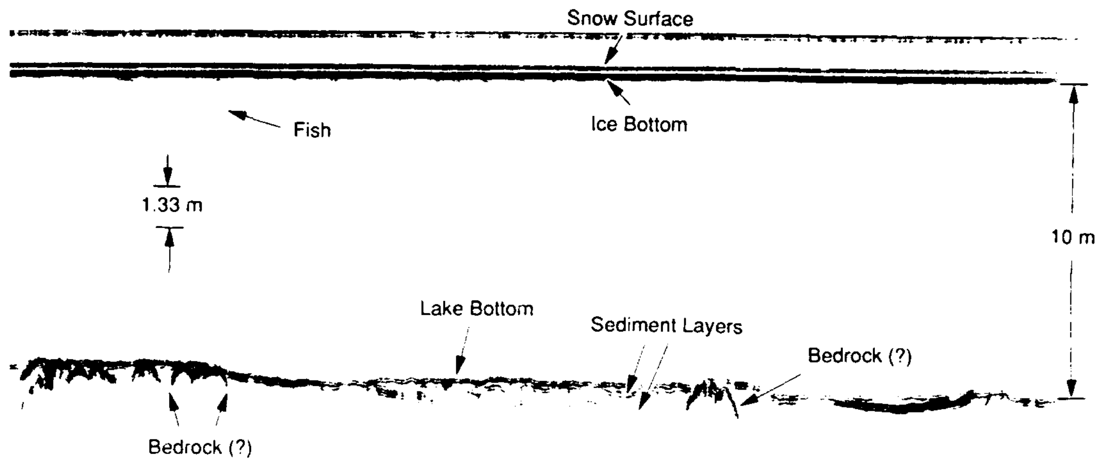


Figure 7. Approximately 300-m-long radar sounding of lake bed relief to the west of the survey line. Note the sediment layers and apparent bedrock and fish signatures.

layer on the lake bottom gradually slopes from about 4.25 m deep, midway between stations 1 and 2, to about 7.5 m deep just before station 7 or near where the bedrock begins to rise above the sediments.

The intermittent band that appears in the radar record below the ice/water interface reflection is a double reflection resulting from excessive receiver gain.

To determine if the lake bed relief varied appreciably on either side of the central portion of the survey line, 25- to 50-m-long radar sounding profiles were run perpendicular to the survey line on each side of stations 2 through 6. These radar records are shown in Figure 6. The records indicate that the lake bed sloped less than 1% perpendicular to the survey line, which also had a slope of less than 1%. Therefore, the radar data indicated no significant lake bed relief variations. This is important because the footprint diameter over which an integrated EMI sounding measurement is made is about 1.3 times the antenna elevation above a conductive interface for the coaxial coil arrangement and about 3.7 times the antenna height for the co-planar coil arrangement (Kovacs et al. in prep.). Since much of the route was over gradually sloping bed topography, the EMI data were not distorted in this area by a severely sloping or hummocky lake bottom.

Another radar sounding record was made to the west of the survey line. This deeper area of the lake was also found to be devoid of significant bottom relief. A portion of this sounding run is shown in Figure 7. Note the apparent fish signature in this record, the sediment layers and the apparent bedrock signatures.

After the radar survey profiles were made, a helicopter towing the EMI sounding system was flown down the survey line. The EMI data were analyzed using a generalized one-dimensional layered-halfspace inversion routine, coupled with a fast but general forward model. It became apparent that the highly magnetic rock units known to exist in the surrounding Sudbury-Brent area of Ontario had affected the electromagnetic response measured at Lake Nipissing. This made EMI water depth determination for this lake difficult at best.

It is always desirable in data inversion prob-

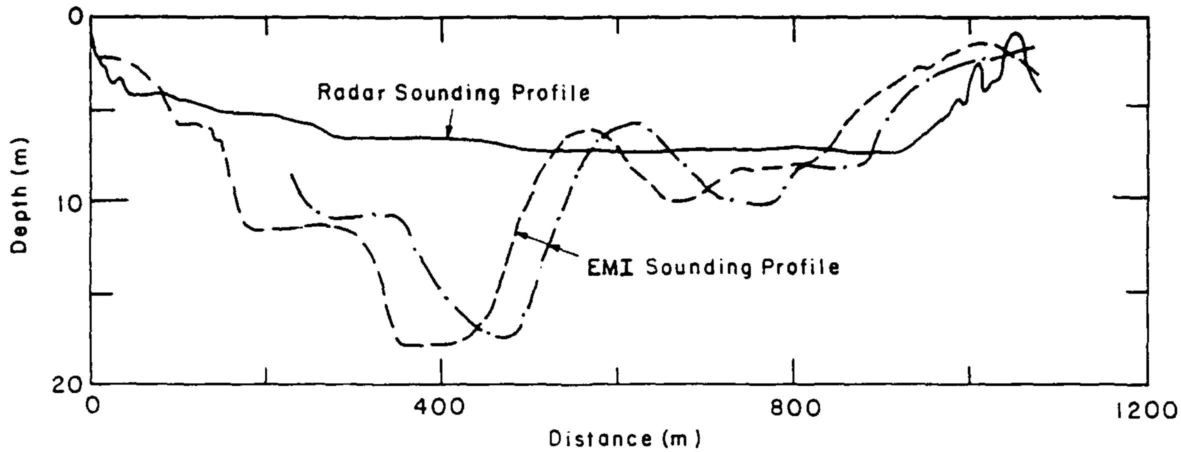


Figure 8. Electromagnetic induction vs. radar profiles of bathymetry along Lake Nipissing survey line. Lack of agreement between the EMI data and the verified radar depth data is apparent.

lems to minimize the number of parameters that are "free" (to be determined). The most reasonable model for the Lake Nipissing data included a 0.9-m-thick layer of snow plus ice, with zero conductivity, underlain by water tested to have a conductivity of 4.3 mS/m at 0°C, which in turn overlay a uniform halfspace. Free parameters in the model were the water thickness and the apparent bottom conductivity.

The results of this analysis for two of the EMI sounding flights are shown in Figure 8, along with a cross section of the lake along the track line as determined by radar sounding. Clearly, there is little agreement between the EMI and the radar sounding results. The EMI results were apparently affected by the highly magnetic bedrock in the lake bed, which indicates that EMI sounding of freshwater lake depths in this geologic setting is problematic. However, helicopter-borne EMI sounding of freshwater bathymetry in other geologic environments is still very reasonable, especially in a setting where the bed material is composed of a deep layer of clay. This material should produce a strong conductivity contrast at the lake bed/water interface and allow for a good estimate to be made of the bird-to-lake bed distance.

DISCUSSION AND CONCLUSIONS

As expected, radar sounding of through-the-ice bathymetry provided depths that were in excellent agreement with the tape-measured distances. Sediment layers and apparent bedrock features in the lake bottom were also detected.

The helicopter-borne EMI sounding results did not conform with the radar-determined lake bottom relief. EMI profiles were in general agreement with one another, indicating that the broad variations in these profiles were not simply caused by some form of noise or system drift. It appears that the EMI system was profiling some kind of topographic or electromagnetic interface. Whether this was the sediment/bedrock interface, a magnetic bedrock effect or an intermediate conductive layer is unknown.

Helicopter-borne EMI sounding will not be suitable for extracting accurate bathymetry where there is little conductivity contrast between the water and the bed material. This is particularly true for low frequency EMI sounding at less than 30 kHz, where the measured response is not particularly sensitive to the low sediment/water interface conductivities typical of freshwater environments. However, in water bodies with thick clay-rich sediments, there will be more electromagnetic contrast at the water/sediment interface, which should be very amenable to airborne EMI bathymetry sounding. This will be especially true with the use of a higher frequency wideband EMI system which would allow for more frequencies to be selected for analysis as well as the use of frequencies in the 50- to 150-kHz range. This broadband capability would be very useful for determining freshwater bathymetry and in reducing the error in the estimated depth.

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13. ABSTRACT (*Maximum 200 words*)

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